

Final Report

**Cumulative and Synergistic Effects of Physical, Biological, and
Acoustic Signals on Marine Mammal Habitat Use**

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Award Number: N00014-08-1-0394

Physical Oceanography Component

Soundscapes Under Sea Ice: Can we listen for open water?

LONG-TERM GOALS

The long-term goal of this collaborative research effort is to enhance the understanding of how variability in physical, biological, and acoustic signals impact marine mammal habitat use. This is especially critical in areas like the Bering Sea where global climate change can lead to rapid changes of the entire ecosystem. The Arctic is projected to experience ice-free summers within 30 years (Wang & Overland, 2009). This will have significant impacts for the natural ecosystem dynamics and human use associated with transportation, fishing, military activity, and energy exploration. Baseline measurements will play an important role in mitigation efforts and environmental assessments as military activity increases in the region. A major component of this research is to use passive ambient sound to identify the physical environment present, and then to use this information to interpret the biological data collected.

OBJECTIVES

The objectives of the passive acoustic component of this collaborative research effort are to identify and make synoptic measurements of the physical environment that the marine mammals (whales and seals) are using. Attention to the physical environment is often absent from biological studies and yet is an important component of biological processes. Physical oceanographic processes, including wave breaking, rainfall and sea ice processes, all have distinctive acoustic signatures that can be used to detect, classify and quantify them. Learning to identify physical processes acoustically will be an important aid to more encompassing ecosystem studies. Furthermore, ambient noise levels in the Bering Sea are measured directly and provide a background baseline for future studies and operations. Long-term measurements will play an important role in determining the point at which cumulative effects of the environment and human activities impact animal populations, and in identifying the kinds of

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 28 OCT 2013		2. REPORT TYPE		3. DATES COVERED	
4. TITLE AND SUBTITLE Cumulative and Synergistic Effects of Physical, Biological, and Acoustic Signals on Marine Mammal Habitat Use				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Applied Physics Laboratory, University of Washington, 1013 NE 40th Street, Seattle, WA, 98105				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited.					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

exposure that pose the greatest risk. The Bering Sea is an ecosystem that is presently experiencing rapid climate change, has relatively healthy populations of cetaceans and seals, and supports the largest fishery in the US EEZ.

One especially interesting component of the Bering Sea ecosystem is that it is ice-covered for part of the year. Understanding how marine mammals interact with sea ice is particularly difficult to study as the environment is extremely difficult to sample by more traditional means such as ship cruises or maintaining surface moorings. In fact, NOAA does not attempt to maintain surface moorings during most of the year because of the threat of sea ice, and other harsh conditions. Acoustic sampling of this environment offers the possibility to extend measurements of the environment throughout the year.

The passive identification of ice types present has applications outside of the marine mammal community. In particular, by identifying the presence or absence of surface ice, remote oceanographic instrumentation platforms, including drifters, sea gliders and sub-surface moorings can be allowed to surface in safe conditions (no ice) and report data back to users. This will allow potential data collection in remote ice-covered regions where data collection is sparse, and thus greatly expand knowledge of these environments. Data collected as part of this project can be used to address this question: Can we listen for open water?

APPROACH

The instrument used to collect the passive acoustic data (Passive Aquatic Listener – PAL) is an adaptive recorder that records ambient sound pressure levels (SPL) between 100 Hz and 50 kHz with a time step of 1-5 minutes depending on the background sound source that is identified. It also records selected sound samples (4.5 seconds in length at 100 kHz sampling) containing transient signals such as animal vocalizations and ice cracking. The sound samples have been used to identify the animals that are present (Miksis-Olds et al. 2010). The time series of SPLs are used to evaluate the background physical conditions, including wind speed, rainfall and ice conditions.

Different sound sources produce unique sound signatures that can be used to identify the source. These different sounds can be described as “soundscapes”, and graphically represented by comparing two or more features of the sound field, such as SPL levels at different frequencies or spectral slopes between selected frequencies (Figure 1). Soundscapes are persistent on the time scale of hours to days, but can change rapidly if the environment conditions change. Data were collected during the winter season of 2008-2009 at the M5 mooring maintained by NOAA on the continental shelf in the Bering Sea, near St. Matthew’s Island (Stabeno et al., 2012). This is a sub-surface mooring during the winter. The water depth is 70 m. By tracking the changes in the soundscape at the M5 mooring throughout the seasonal ice cover (January to May), periods of “open water” can be detected.

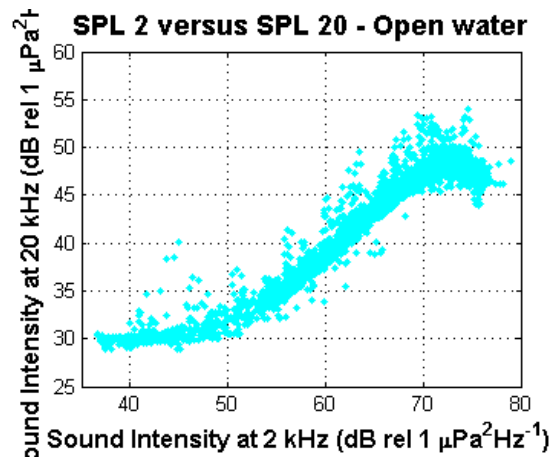


Figure 1. The soundscape of open water. This shows the relationship of sound pressure level (SPL) at 2 and 20 kHz for open water conditions during the month of November 2008 at the M5 mooring in the Bering Sea.

RESULTS

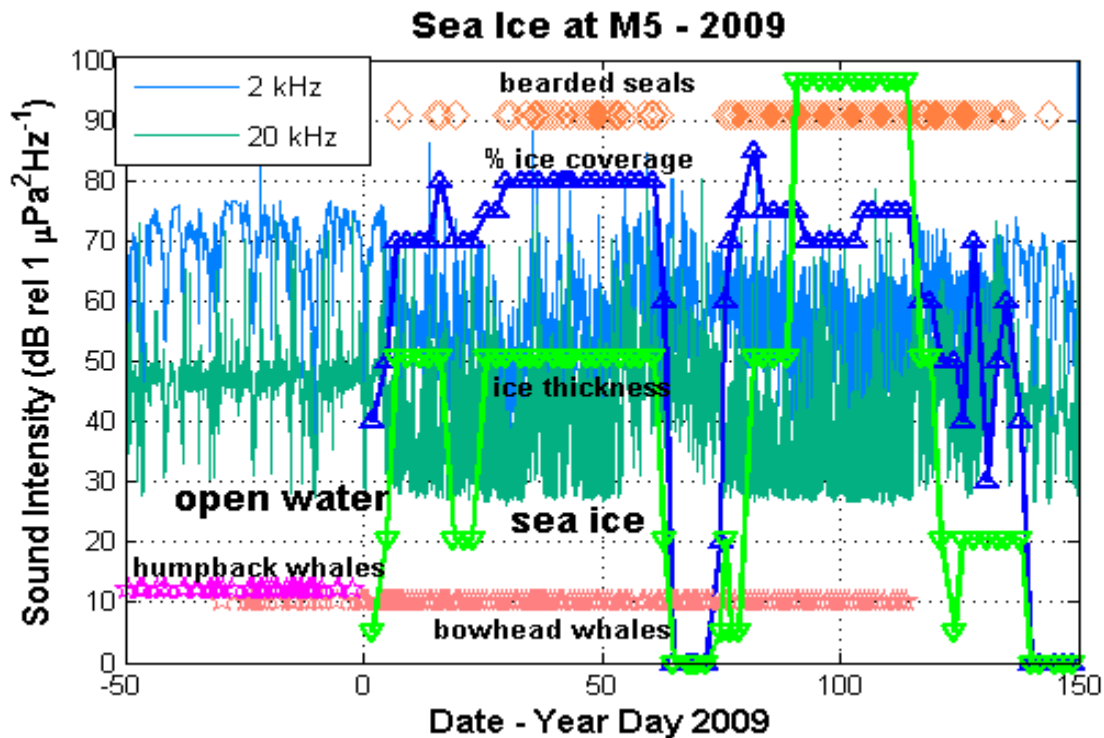


Figure 2. Overview of sea ice conditions during the winter of 2008-2009 at Mooring M5. Sound levels at 2 and 20 kHz are displayed, showing ice onset on Jan 5 and ending on May 17 (Days 5-137). Also shown are animal choruses, including humpback whale (an open water species), bowhead whale (associated with sea ice) and bearded seal (associated with thicker sea ice). Sea ice coverage (%) and ice thickness (in cm) are from satellite measurements. An interlude of relatively open water occurred from Feb 24 to Mar 15 (Days 55-74).

The 2008-2009 data from the M5 mooring demonstrated at least five different soundscapes associated with sea ice coverage. This includes physical ice sounds, and the sounds of marine mammals associated with sea ice, especially bowhead whales, bearded seals, ribbon seals and

walrus. The ice pack was present at M5 from 5 Jan to 17 May 2009 (Days 5-137). This ice season at M5 had an interesting interlude in late February/ early March when the ice pulled back to the north for about 20 days (24 Feb – 16 Mar). This episode was detected acoustically, including the acoustic soundscape of open water on Feb 26/27 (Days 57/58) and 10 Mar (Day 69), and caused an anomalous change in zooplankton activity (Miksis-Olds et al., 2013). The interlude ended abruptly on 16 Mar (Day 75) when thick, continuous pack ice returned and persisted until mid-May.

The seasonal onset of sea ice is clearly detected in the sound record. The PAL was programmed to detect and record transient sounds if they occurred. A transient sound was defined as a sound lasting less than 4.5 seconds, the time length for a single PAL sample. During open water conditions relatively few transient sounds were detected, mostly from humpback, fin and killer whales. But as the ice formed, bowhead whales, closely associated with sea ice, become the principal source of triggering. These animals are very vocal, nearly ubiquitous, with choruses lasting hours and causing the number of transient sound detected by the PAL to rise from less than 1 per hour to over 5 per hour. The physical sounds associated with sea ice forming, a bizarre squeaking sound, and the sound of ice floes banging together are also detected at this time.

As the ice coverage increases and floes merge in to a sheet of ice, variable relatively loud sound levels of ice floes banging (ice floe soundscape) are interspersed with the very quiet high frequency sound levels of a solid ice sheet (solid ice soundscape). The sounds associated with the whales continue, mostly below 5 kHz. On Day 25 the ice pack becomes solid. The sounds of the ice seals, especially bearded, ribbon and walrus are being detected. In particular, the bearded seal chorus starts about Day 30. These animals are known to breed on the ice, and in the case of bearded seals, their calling is ubiquitous, and appears to be a proxy for thicker sea ice, and part of the soundscape for this location (Bering Sea) and season (ice seals breeding).

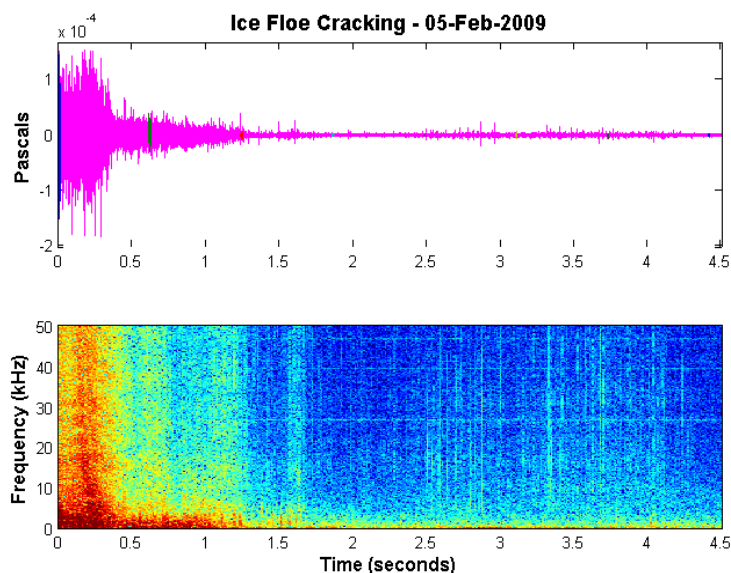


Figure 3. The shotgun-like sound of the solid ice sheet cracking on Day 36 (Feb 5). At this time the soundscape changes from solid ice to floe-banging.

The top panel shows the underwater sound pressure recorded in Pascals. The bottom panel show the spectrogram from 0-50 kHz, with red the loudest ($90 \text{ dB rel to } 1 \mu\text{Pa}^2\text{Hz}^{-1}$), and blue the quietest ($30 \text{ dB rel to } 1 \mu\text{Pa}^2\text{Hz}^{-1}$).

On Day 36, a very loud cracking noise, like a shotgun, is recorded (Fig. 3). This sound clip is the ice sheet breaking, and an open water lead forming. Floe banging is subsequently detected, confirming the soundscape for floe banging. This is relatively loud at all frequencies. The ice seals and bowhead whale calls continue.

Another interesting soundscape of sea ice is a “fizzing” sound with relatively high levels of high frequency sound content. This is apparently the sound of melting ice in water, perhaps small bits of ice melting. It is speculated that the sound is coming from bubbles popping into the water as the ice melts. It is relatively loud at the higher frequencies (over 20 kHz), suggesting that the bubbles being injected into the water are relatively small (less than 150 μm radius). A similar soundscape has been recorded in coastal fjords with tidewater glaciers (glaciers that are discharging ice bergs and bits directly into the water) (Pettit et al., 2012).

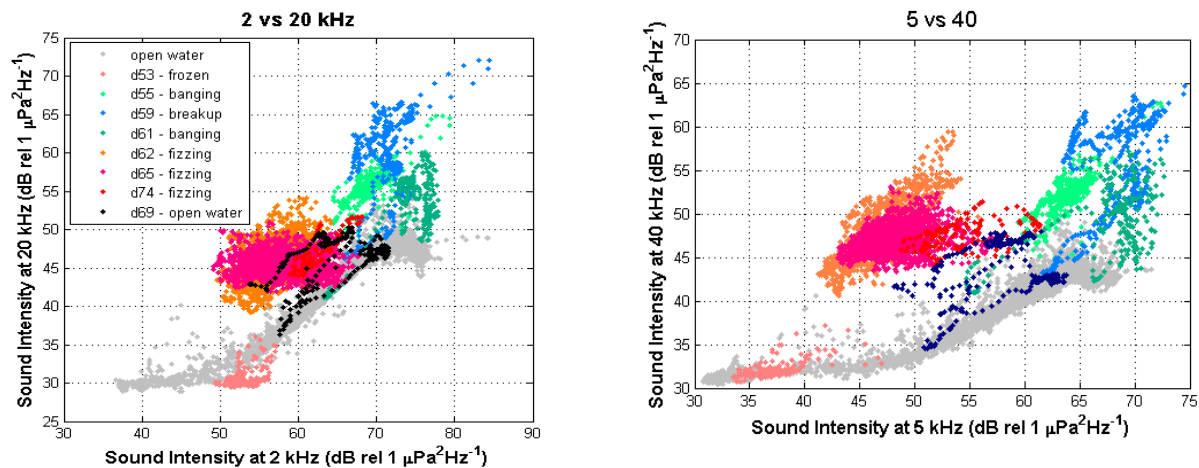


Figure 4. Soundscapes during the sea ice retreat from Feb 24th to Mar 16th (Days 55-75). The open water soundscape is shown in gray; floe-banging soundscapes are shown in green/blue; ice fizzing (melting) soundscapes are shown in orange/red; solid ice soundscape in salmon color. The black points show a 20-hour sequence of the soundscape changing on Mar 10th (Day 69) from open water to ice fizzing.

On Feb 24th, the ice pack breaks again, and retreats to the north. Soundscapes for floe banging, fizzing and open water are detected acoustically. Figure 4 shows the changes in soundscapes during this ice retreat interval. On Feb 26th (Day 57), the open water soundscape is detected. The bearded seal vocalizations are suddenly absent, as are bowhead whales, suggesting that even the ice edge is distant from the M5 mooring, that is, open water is present. And active acoustic soundings record the start of an unexpected change in zooplankton activity (Miksis-Olds et al., 2013). Satellite coverage at the M5 mooring does not show a drop in ice coverage or thickness until March 2nd, several days later. The soundscapes of floe bumping and fizzing alternate for several days. On March 10th (Day 69), open water soundscapes are again detected. During this period, most of the soundscapes are not open water, but rather the sounds of floe bumping and ice fizzing, suggesting icy water, but with only small floes (pieces of ice) present. The acoustic record suggests longer open water conditions than reported by the satellite data, starting sooner (Day 57) but ending on the same date (Day 75). During most of

the interlude bowhead whales and walrus are still detected, suggesting that there is sea ice nearby. However the other ice seals, in particular, ribbon and bearded seals, are not recorded during this period, suggesting that solid ice sheets are not present at the mooring location.

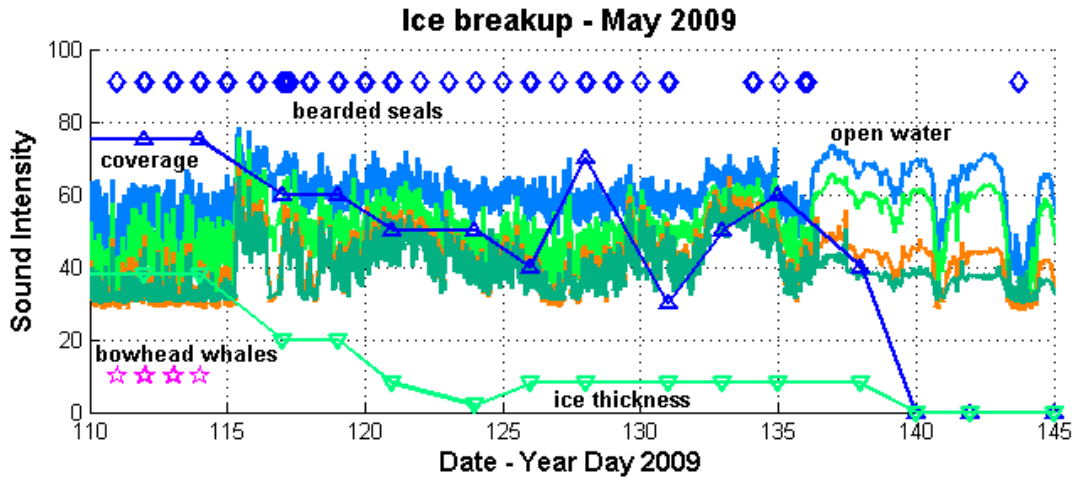


Figure 5. Seasonal sea ice breakup at Mooring M5. The solid ice sheet cracks on Apr 25th (Day 115). Soundscapes of floe banging and ice fizzing alternate until May 17th (Day 137) when the open water soundscape returns for the season. The bowhead whales migrate north, with their chorus ending on Apr 24th (Day 114). The bearded seal chorus persists until the ice cover ends on Day 137. Shown are the sound levels at 1, 5, 20 and 40 kHz, together with ice coverage (%) and thickness (inches).

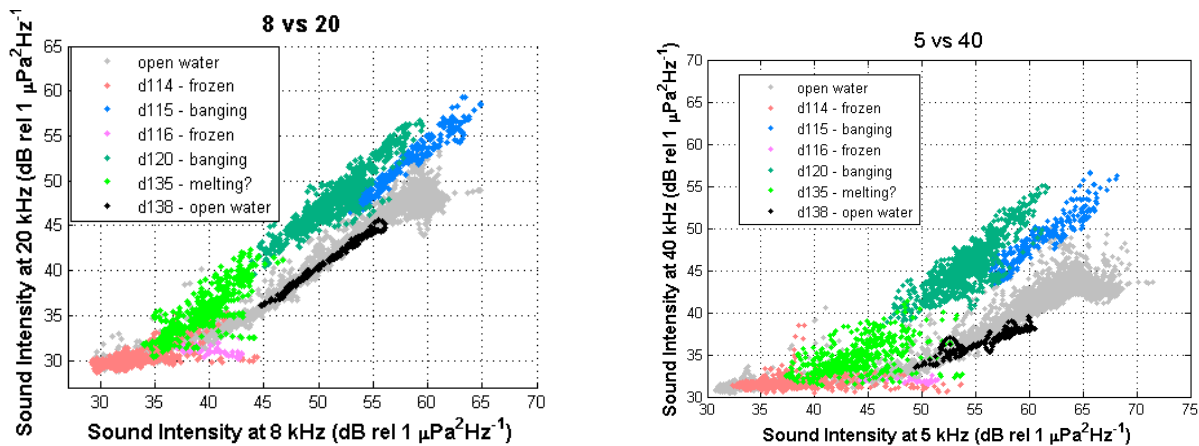


Figure 6. Sea ice soundscapes during the seasonal ice breakup (Days 115-136). Relatively quieter ice floe banging (blue) and fizzing (greens) characterize these soundscapes. Open water (gray from Dec 2008) and open water from May 17th (Day 137, black) are shown for comparison.

Thick ice conditions returned abruptly on Mar 16th (Day 75) and persist until the seasonal ice breakup starts in on April 25th (Day 115), with open water finally appearing on May 17th (Day 137). This sequence is easily observed in the temporal passive acoustic record (Fig. 5), and by changes in the soundscape (Fig. 6). The bearded and ribbon seals are once again detected acoustically and the satellite observations show a return of the sea ice. The soundscape is the

soundscape for solid ice coverage. This condition remains present until April 25th, when loud floe banging is once again detected. The solid ice sheet has apparently broken, and the seasonal breakup of the ice has begun. The bowhead whales detections finally disappear as these mammals begin their annual migration to the Arctic Ocean. The soundscape shows loud floe-banging conditions mixed with periods of fizzing. Ice seals continue to be detected until the ice disappears on May 17th (Day 137). After May 17th, only open water soundscapes are recorded, including the resumed detection of open water animal species, including killer and beluga whales.

CONCLUSIONS

At least five distinctive sea ice soundscapes have been detected in the M5 mooring data. These soundscapes are distinctive and are indicative of different sea ice conditions at the ocean surface. The distinctive open water soundscape was detected during the sea ice retreat in March, and indicates an earlier onset and longer duration than the satellite data for this episode. The sound of fizzing during melting suggests that the sea surface was covered by small bits of ice. Validation of the exact sea ice conditions during the sea ice retreat and the ultimate sea breakup may confirm this speculation.

It is clear from these data, that the sound of open water can be used to find open water surface conditions. The soundscape of solid ice and floe banging, potentially destructive for ocean instrumentation, can be used to predict when sub-surface instrumentation packages should be allowed to surface and report data to shore. It is not known if the sound of fizzing is also an ocean surface condition that allows instrumentation to surface safely or not.

IMPACT and APPLICATIONS

The acoustic measurement system used in this project has the advantage of being deployed for long periods of time on subsurface moorings, affording the opportunity to collect valuable data during the harsh conditions of the winter season when traditional sampling techniques are not possible. The combination of year-round acoustic data collected with the active-passive acoustic system, hydrographic data collected by NOAA mooring sensors, and biological samples collected during each research cruise afford the opportunity to apply the acoustics to a large spectrum of scientific questions.

The passive identification of ice types present has significant applications outside of the marine mammal community. In particular, by identifying the presence or absence of surface ice, remote oceanographic instrumentation platforms, including drifters, sea gliders and sub-surface moorings can be allowed to surface in safe conditions (no ice) and report data back to users. This will allow potential data collection in remote ice-covered regions where data collection is sparse, and thus greatly expand knowledge of these environments.

The system used in this study is appropriate for use in almost all marine environments. It provides an advantage over continuous recording instruments in that the initial real-time

processing of environmental sound by the PALs detect and identify sources of interest without an overwhelming amount of data needing post-processing.

TRANSITIONS

Underwater ambient sound contains quantifiable information about the marine environment, especially sea surface conditions including wind speed, rainfall rate and type, and sea state conditions (bubbles), and now, the presence or absence of sea ice. Mostly this information is unused by oceanographers and the Navy. This project represents a transition from the study of ambient sounds themselves into the application of the physical environment inferred from the ambient sound as an aid for the interpretation of other types of data collected in the same environment. This is a fundamental advance for practical use of passive acoustic monitoring of the underwater marine environment.

RELATED PROJECTS

The ONR-supported project “Monitoring sea surface processes using high frequency ambient sound”, N00014-04-1-099, has as its principal goal to make passive acoustic monitoring of the marine environment an accepted quantitative tool for measuring sea surface conditions (wind speed, rainfall and sea state), monitoring for the presence and identity of marine wildlife (especially whales), and monitoring anthropogenic activities including shipping, sonar and other industrial activities.

Several NOAA-supported projects, including Passive Acoustic monitoring of killer and beluga whales at the Barren Islands, Alaska, the Bering Sea Acoustic Report (Nystuen et al, 2010), Marine Mammal Monitoring for NW Fisheries (Nystuen et al. 2007), and Monitoring killer whale predation at Stellar Sea Lion rookeries in the Aleutian Islands, use PALs as the principal monitoring instrument for the description of the environment and for the detection and identification of marine cetaceans and other marine animals. This project benefits directly from the data collection strategies and interpretation developed for these projects.

REFERENCES

Miksis-Olds, J.L., Nystuen, J.A., Parks, S.E., 2010. Detecting marine mammals with an adaptive sub-sampling recorder in the Bering Sea. *Journal of Applied Acoustics* 71, 1087-1092.

Miksis-Olds, J.L., Stabeno, P.J., Napp, J.M., Pinchuk, A., Nystuen, J.A., Warren, J.D., Denes, S.L. (2013). “Ecosystem response to a temporary sea ice retreat in the Bering Sea.” *Progress in Oceanography*.

Nystuen, J.A., M.B. Hanson and C. Emmons, 2007: “Listening for killer whales in the coastal waters of the NE Pacific Ocean”, 2nd International Underwater Acoustic Measurements Conference, Heraklion, Crete, June 2007.

Nystuen, J.A., P.J. Stabeno and S.E. Moore, 2010 "A sound budget for the southeastern Bering Sea: measuring wind, rainfall, shipping and other sources of underwater sound", *J.Acoust.Soc.Am.* **128**, 58-65.

Pettit, E.C., Nystuen, J. A., and O'Neel, S., 2012 "Listening to Glaciers: Passive Hydroacoustics Near Marine-Terminating Glaciers", *Oceanography*, vol. **25**.

Stabeno, P.J, Falry, E.V., Kachel, N.B., Moore, S., Mordy, C.W., Napp, J.M., Oveland, J.E., Pinchuk, A.I., Sigler, M.F. (2012). "A comparison of the physics of the northern and southern shelves of the eastern Bering Sea and some implications for the ecosystem." *Deep- Sea Research II*, doi:10.1016/j.dsr2.2012.02.019.

Wang, M., Overland, JE. (2009). A sea ice free Arctic within 30 years? *Geophysical Research Letters* 36: L07502.

PUBLICATIONS

Nystuen, JA, Miksis-Olds, JL, Stabeno, PJ (in prep). Soundscapes under sea ice. *Journal of the Acoustical Society of America*.

Denes, SL, Miksis-Olds, JL, Mellinger, DK, Nystuen, JA. (submitted 6/2012). A comparison of marine mammal detections from two non-continuous autonomous acoustic recording systems: comparison of sub-sampled acoustic classifications. Special Issue on Methods for Marine Mammal Passive Acoustics, *Journal of the Acoustical Society of America*. [refereed]

Miksis-Olds, JL, Stabeno, PJ, Napp, JM, Pinchuk, A, Nystuen, JA, Warren, JD, Denes, SL. (published) Ecosystem response to a temporary sea ice retreat in the Bering Sea. *Progress in Oceanography*. [refereed]

Miksis-Olds, JL, Nystuen, JA, Parks, SE (2012). What does ecosystem acoustics reveal about marine mammals in the Bering Sea? In: *Effects of Noise on Aquatic Life*. A.N. Popper and A. Hawkins eds., Springer Science + Business Media, LLC. Pp 595-598.

Miksis-Olds, JL, Nystuen, JA, Parks, SE. (2010). Detecting marine mammals with an adaptive sub-sampling recorder in the Bering Sea. *Journal of Applied Acoustics* 71: 1087-1092. DOI:10.1016/j.apacoust.2010.05.010. [refereed]

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)				8. PERFORMING ORGANIZATION REPORT NUMBER	
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12. DISTRIBUTION/AVAILABILITY STATEMENT					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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